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Laboratory Bench to Test ZEBRA Battery Plus Super-Capacitor Based Propulsion Systems for Urban Electric Transportation

Clemente Capasso, Ottorino Veneri*

Istituto Motori - CNR National Research Council, Via G. Marconi 4, 80125 Naples, (Italy)

Abstract

In this paper a laboratory 1:1 scale test bench to perform experimental analysis on a Zebra battery plus super-capacitor based propulsion systems for electric urban transportation means is presented. The analyzed case study is focused on a 70 kW electric drive, specifically manufactured for electric urban road applications, supplied by a parallel of two 550 V - 38 Ah Zebra batteries and a 63 F super-capacitors bank. The electric power train is connected, through a fixed ratio gear box, to a 100 kW regenerative electric brake provided with speed and torque controls, in order to evaluate the propulsion system performance in steady state and dynamic operative conditions. The two different storage systems can be tested when working together and providing the required power to the electric drive, with different contributions by each storage device in terms of electric energy and power. In addition, different control strategies can be experimentally evaluated, depending on the tested driving cycle and with reference to a specific vehicle under study. For the above configuration, an evaluation of the real vehicle performance, in various operative road conditions, can find a validation through this laboratory dynamic test bench. Finally, this experimental procedure to characterize and study electric power trains supplied by different kinds of storage systems highlights the real potentialities for manufacturers of electric vehicle in taking advantage of laboratory experimentations on the electric power-train, in order to support their design processes. The content of this paper represents a knowledge base to carry out experimental results, which are object of following studies.

Keywords: Batteries; Electric Vheicles; Super capacitors; Dynamic Test Bench

* Corresponding author. Tel.: +39 081 7177143; fax: +39 081 2396097.
E-mail address: o.veneri@im.cnr.it.

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1. Introduction

Nowadays, traditional road transportation systems are considered as the main responsible for the significant increase of air pollutants, including carbon monoxide, carbon dioxide, hydrocarbons, nitrogen oxides, and particulate matter. This phenomenon, which is particularly relevant in urban areas, is widely recognized as affecting the life quality of critical groups of people, such as the elderly and children, and in some cases drawing the consequence of a significant reduction in life span [1]. One of the effective pathways to address the above issues is certainly represented by the adoption of high efficiency power train technologies, such as hybrid and fully-electrified vehicles (EVs). In particular, hybrid vehicles have recently found a good consumer acceptance, reaching a market share of 1.4 % in the European countries. On the other hand, the EVs market penetration still remains very slow, for the well known reasons of limited travel ranges, which are often not compatible with the common user needs [2]. In fact, most of the private users generally consider inconvenient the use of electric transport means, and only suitable for short trips as 'second vehicle'. Anyway, recent developments in new technologies of battery and power electronic have largely supported the diffusion of EVs in the field of urban road transportation means, where recent legislations have granted retrofitting operations and corporate/public fleet electrifications. In addition, in many urban context electric transportation means are required to operate in historical centres or congestion charge zones, where no emission is allowed [3, 4].

Among battery technologies, lithium compounds have been investigated as energy storage system for EVs in different papers, showing good performance in terms of charging/discharging rate and efficiency, energy and power density and durability [5, 6]. Nevertheless this technology is mainly affected by cost, safety and environmental issues, which need to be taken into account especially in case of a large-scale adoption of lithium-based energy storage systems [7, 8]. The above issues justify the growing interest of the researchers towards alternative solutions based on lithium-free compounds. Among those, the sodium-nickel chloride batteries, also referred with the acronym ZEBRA (Zeolite Battery Research Africa), are considered worthy of investigation, mainly for the recognised good performance in supplying EVs, with additional advantages in terms of initial and maintenance costs, environmental impacts and high coulombic efficiency in any climate condition. On the other hand, ZEBRA batteries are characterized by low values of power density with respect to recent lithium technologies, with consequences on electric power-train performance during peak power demands or regenerative braking operations. This deficiency of sodium-nickel chloride batteries can be overcome by using hybrid energy storage configurations, which integrate, for example, supercapacitors with the considered ZEBRA battery technology. High power density supercapacitors are expected to improve in this way the whole power train performance.

The use of Electrical Double Layer Capacitors (EDLC) for EV applications has been widely considered in the scientific literature [9]. This interest is mainly justified by their specific characteristic of combining high power density, reliability and durability with energy density values, which result very high in comparison to traditional electrostatic and electrolytic capacitors. In fact the porous structures of their electrode surface enable high values of capacitance per unit volume, with an equivalent useful area up to 2000 m^2/cm^3 [9 - 11].

The above considerations draw the attention of this paper to the case study of an urban electric mini-bus supplied by a ZEBRA battery plus super-capacitor hybrid storage system,. The base architecture for this kind of vehicle is reported in the block scheme of Figure 1. In particular, the block scheme shows the main components of the power-train, such as the hybrid energy storage system, the electric drive, the transmission system and the on board battery charger.

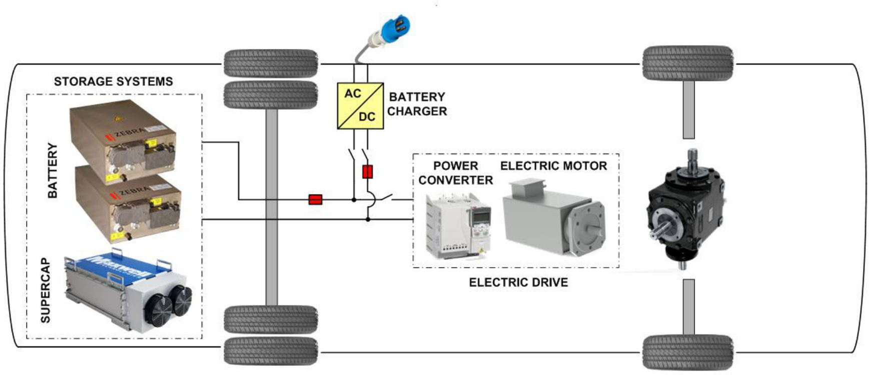

Fig.1. Block diagram of the propulsion architecture for an electric urban bus.

The analysis of these kinds of power train architecture, using road vehicle prototypes since the beginning of their study and design procedure, generally implies the necessity of facing a great number of issues, specifically in terms of measurement and control of the fundamental parameters, related to the real working conditions of a vehicle on the road, mechanical solicitations and safety in general. These issues can be easily simplified, especially in case of retrofit applications, when the real performance of the whole propulsion system is evaluated on laboratory test benches.

The test bench system, whose characteristics are reported in this paper, enables the experimental analysis to show the real performance of an electric power train, proposed and designed by an electric vehicle manufacturer and supplied by an energy storage system based on a Zebra battery pack and super capacitor, to power urban vehicles such as mini-buses or similar kinds of road vehicles. The laboratory experimental results, which can be obtained through this analysis, are expected to show how important is the preliminary test of power trains on laboratory test benches, in order to verify the right design of the main components in terms of their characteristics. On the other hand the obtained results from this analysis intend to support the lack of knowledge in the literature about of this kind of experimental applications. In addition these results can be used as an experimental knowledge base for the development and validation of simulation models of urban vehicles.

2. Experimental set-up

A laboratory test bench has been set up to run experimental tests on propulsion systems for electric urban transportation means, powered by hybrid energy storage systems combining ZEBRA batteries and EDLC.

In Figure 2 the block scheme of electric power train working on the laboratory test bench is shown. The considered power train is composed by a 70 kW induction electric drive, controlled through an AC/DC bidirectional converter and supplied by the above hybrid energy storage system. The integration of the EDLC with the DC-link is realized by means of a controlled DC/DC bidirectional power converter. Moreover a dynamic asynchronous brake is coupled with the traction motor through a transmission gear, characterized by the two different gear ratios (1:3 or 1:6), which can be manually set depending on vehicle parameters and expected road slope. This system makes possible the laboratory simulation of the real vehicle inertia and resistant forces directly reported to the wheel shaft. The dynamic brake is able to take/feed back the electric energy from/towards the main grid during the laboratory tests by means of its IGBT based bidirectional conversion architecture.

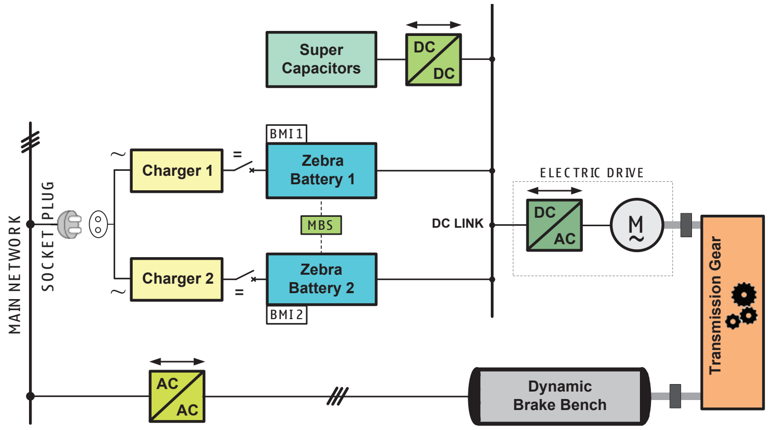

Fig. 2. Block scheme of the laboratory test bench

For the architecture analyzed in this paper two identical 550V - 38 Ah ZEBRA batteries, connected in electric parallel, are considered. Those batteries are equipped with a specific Battery Management Interface (BMI), which is devoted to monitoring and control operations, such as: cell voltage balancing, under/over voltage protection, charging/discharging current limitation, battery temperature control. Moreover the BMI, during the charging operations, periodically performs battery insulation and state of health tests by measuring the battery open circuit voltage, in order to evaluate the number of failed cells. The electrical parallel is managed through a Multiple Battery System (MBS), which communicates, via CAN Bus, with the electric drive control system. In this way the operative conditions of traction system can be easily related to the proper limitations of the main battery parameters, such as battery State of Charge, temperature and charging discharging current. The main characteristics of each ZEBRA battery are reported in Table 1 [12, 13].

Table 1 Main characteristics of each ZEBRA battery

Battery Chemistry	Sodium/Nichel Cloride
Battery Cell Code	ML3X-38
Rated Capacity [Ah]	38
Rated Energy [kWh]	21.2
Open Circuit Voltage [V]	557
Peak Discharging Current [A]	112
Numbers of Cells	216
Maximum Charging Voltage [V]	2,67
Minimum Discharging Voltage [V]	1,17

The bidirectional DC/DC power converter, realizing the integration of EDLC with the DC Link, is a three-leg converter based on IGBTs technology and controlled through specific PWM techniques, in order to manage the energy fluxes, from and towards the EDLC, in different operative conditions. In this way it is possible a selection, by a supervising unit, among different energy management strategies based on the tracking of supercapacitor charging/discharging current, DC-Link current and DC-link voltage.

The EDLC bank considered in this paper is a 63 F – 125 V supercapacitor module supplied by Maxwell Technologies. The module is equipped with an embedded control unit, which features cell voltage balancing, over/under voltage protection and temperature monitoring. Moreover the control unit can communicate, via CAN bus, with a laboratory computer or other supervising units, giving information about the module working conditions and voltage values for each group of 8 cells. The main characteristics and operative conditions of the supercapacitor module are reported in Table 2.

Table 2 Main characteristics of the super capacitor module.

Rated Capacitance [F]	63
Rated Voltage [V]	125
Absolute Maximum Voltage [V]	136
Maximum Continuous @ ΔT = 15 °C [A]	140
Maximum Continuous @ ΔT = 40 °C [A]	240
Operative Temperature [°C]	-40 ÷ 65
Storage Temperature [°C]	-40 ÷ 70

In Figure 3 a picture of the laboratory racks containing the ZEBRA batteries and super capacitor bank, is shown. The racks also include battery chargers, ZEBRA battery cooling systems and the bidirectional DC/DC converter with its related inductances.

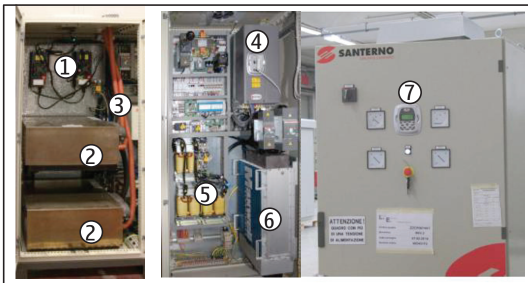

Fig. 3. Storage systems supplying the power train on the laboratory test bench

The dynamic brake is a 100 kW – 815 Nm induction machine properly controlled by means of a user-friendly software interface. The brake control systems is able to perform different control modes such as: Angular speed [rpm] + Accelerator Position (α) [%]; Torque [Nm] + Accelerator Position (α) [%]; Angular Speed [rpm] + Torque [Nm]; Accelerator Position (α) [%] + Road Resistant Forces; Vehicle Speed [km/h] + Road Resistant Forces. In Figure 4 a picture of the dynamic electric brake connected to the electric drive is shown with details of other components working on the laboratory test bench.

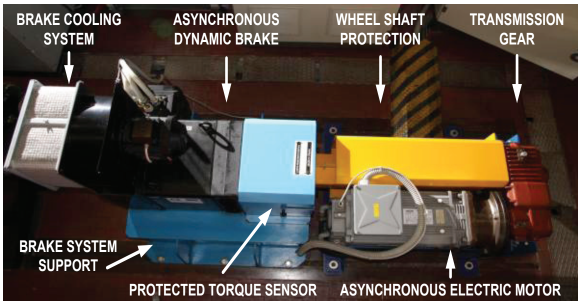

Fig. 4. Dynamic brake connected to the traction induction motor on the laboratory test bench.

Through the above mentioned control modes the dynamic brake and the electric drive can be controlled in order to perform in laboratory standard and real driving cycles for different vehicle and road parameters, such as vehicle weight, inertia, tires, aerodynamic drag coefficient, road surface and slope.

Acquisitions and control systems complete the set up of the test bench and allow a hierarchical management of the whole power train on the test bench.

The research activities on the described test bench identify a methodology to evaluate the performance of innovative hybrid storage systems, when powering road urban transportation vehicles.

3. Conclusion

In this paper a ZEBRA battery plus Electrical Double Layer super-capacitors based propulsion system for urban transport applications is presented, supporting the lack of knowledge on the experimental evaluations in the field of the transportation systems. The proposed experimental set-up is realized by means of a laboratory 1:1 scale test bench, which is able to simulate in a laboratory the real electric power train on real and standard driving cycles. In this way, different aspects related to the real behaviors of the power train can be experimentally evaluated, such as regenerative braking, motor and transmission gear losses. These aspects will be carried out and reported in following publications by the same authors.

Acknowledgements

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Biography

Ottorino Veneri graduated and awarded his PhD in Electrical Engineering by the University of Naples Federico II. Since 2002 he works as a researcher with the Istituto Motori of the National Research Council of Italy. His main fields of interest are the electric drives for transportation systems, electric energy converters, electric energy storage systems and power sources with hydrogen fuel cells.